"DETECT" – A NEW DEFECT DETECTION METHOD AND ITS USE ON SHEET MOULDING COMPOUND (SMC) SUBSTRATES

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ABSTRACT

A novel optical method for detection of surface porosities on SMC substrates is presented. Detection is facilitated by observation of how a liquid film on the surface evaporates. The method utilizes the fact that complete evaporation takes longer time in the pores than elsewhere. The rate of change of a laser speckle pattern gives a measure of the changes at the surface and indicates where pores causes prolonged evaporation. A pilot measurement unit was built that shows that the principle ideas of the system work. Attempts were made to develop the pilot unit so that it could provide quantitative numbers of actual defects on an SMC substrate. The results are encouraging in the sense that the unit can automatically identify areas with higher number of defects.

1. INTRODUCTION

The usage of polymeric composite materials like sheet moulding compounds (SMC) for exterior body panels with Class A surface appearance has increased during recent years. The reasons for this increase are the benefits of SMC-panels in terms of total weight, corrosion resistance and price compared to steel panels. An observed drawback with SMC-panels is however that the risk of having paint defects in the final part is significantly higher for SMC-panels as compared to steel panels. A fundamental reason for paint defects, such as pin holes and blowouts shown in Fig.1, are open surface pores on the composite substrate. These pores are created during the SMC-pressing operation.

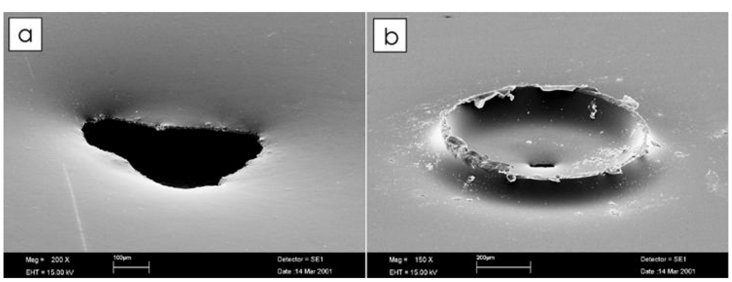

Fig. 1: Typical paint defects in SMC. (a) pinhole (b) blowout (source: [1])

A schematic drawing explaining how small surface porosities ultimately can be magnified and generate larger paint defects is presented in Fig.2. Fig.2.1. shows the simplified surface porosity. Fig 2.2. shows how the liquid paint is applied on the surface so that it covers the entire surface pore. The paint is cured at elevated temperature which causes air and solvent vapour enclosed in the pore to expand, Fig. 2.3. If the generated pressure, at any instance during cure, exceeds the strength of the paint then the paint layer will burst, Fig.2.4 and create a blowout similar to the defect pictured in Fig.1.

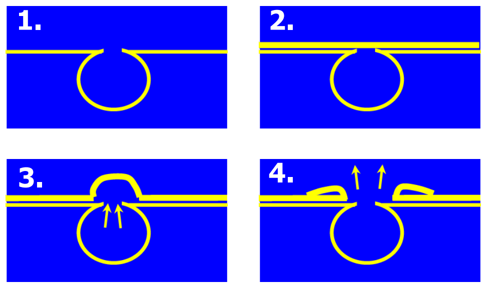

Fig. 2 Schematic drawing of a small surface porosity generating larger paint defect.

It would be of great benefit for the automotive industry if these surface defect generating pores could be discovered as early as possible in the production line. Every refinement step during manufacturing of the painted panel increases the value of the part and significant cost savings could therefore be foreseen if part rejection or rework can be done as early as possible. The current work is interesting in that context since it presents a novel non-destructive optical measurement method – "DETECT" – that has the potential to recognize surface defects on SMC substrates. Such surface pores often cause paint defects in the final part.

2. THEORY AND BASIC PRINCIPLES

The observed surface is illuminated by laser light. Once this laser light is imaged on a CCD-detector a so-called speckle pattern will be created. This speckle pattern is a consequence of interference of the reflected laser light when observed through an optical system. The principal behind the laser speckles is presented in Fig 3. Since the laser speckle pattern can be considered as a fingerprint of the surface texture, one can use this to give information on the rate of film evaporation. An ordinary image based on white light illumination has little or no prospects to provide such information.

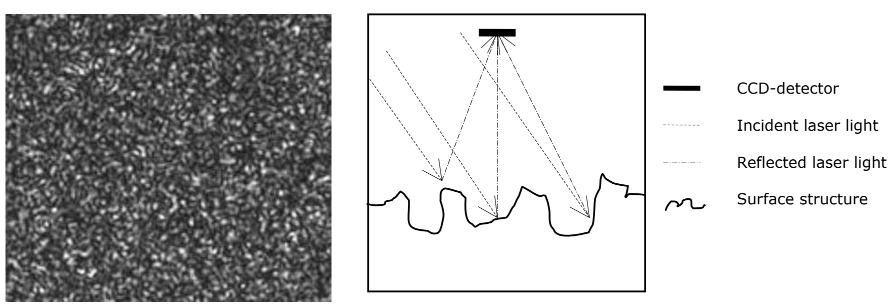

Fig. 3:Left: A laser speckle pattern as it is imaged by a CCD-detector, Right: Principal of optical path differences due to surface roughness

A video stream depicting the evaporation process is used in the analysis. The analysis is made in real time by an in-house developed software. A fundamental part of the measurement method is to determine the amount and rate of change for each pixel [2] in subsequent images. This is done by estimation of the normalized cross-covariance between at least two subsequent images. The value of cross-covariance (or correlation) for each of the *K* subimages of size *N x M* is defined by

$$\langle c \rangle = \frac{\sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{n=1}^{N}\left(I_{1kmn} - \langle I_1 \rangle\right)\cdot\left(I_{2kmn} - \langle I_2 \rangle\right)}{\left(\sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{n=1}^{N}\left(I_{1kmn} - \langle I_1 \rangle\right)^2 \cdot \sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{n=1}^{N}\left(I_{2kmn} - \langle I_2 \rangle\right)^2\right)^{1/2}} \tag{1}$$

where indices 1 and 2 denotes reference and deformed subimage respectively [2]. The variable *I* denotes the intensity of the corresponding pixel. The output from the algorithm is the rate of decorrelation i.e.

$$\left(1 - \langle c \rangle\right) / \Delta t \tag{2}$$

This estimation is performed for all pixels (and or subareas) in the image. If the decorrelation rate is low - i.e. pixels have identical light intensities in subsequent images - then the algorithm yields a value of zero whereas if the rate of change is high then a higher value is obtained i.e. decorrelation between the areas. The algorithm is particularly sensitive and well suited to reveal areas that undergo large microstructural changes. It turns out that the nature of a liquid surface is also stochastic in the sense that it inherently gives high decorrelation rate values when subjected to distributed laser light and analysed with the current analysis. Once the liquid is evaporated from the surface then the speckle pattern becomes constant and subsequent images become and remain highly correlated. Evaporation takes longer time in open pores, hence when analyzed by cross correlation then these areas can be identified. The principal way to detect surface defects with the current method is thus

1. Apply a fluid or moisture on the area of interest
2. Illuminate the area with distributed laser light
3. capture an image with the CCD-camera
4. Analyze the current image together with a fixed number of previous images using the decorrelation algorithm

Processing two or more subsequent images with equations 1 and 2 thus yields in an array containing decorrelation rates. These rates – which ranges between 0 and 1 – will when translated in to greyscale values give images like the one presented in Fig. 4. Black, in the picture corresponds to decorrelation rate of zero i.e. areas where subsequent images remains constant and identical over time. White corresponds to decorrelation rate of 1 i.e. rapidly changing areas. The image presented in Fig. 4 is taken during a sequence where the area covered by fluid or moisture is gradually decreasing through evaporation and drying. Region I in the image corresponds to areas still covered by fluid and where the decorrelation rate is high. The fluid has recently evaporated from the substrate surface of Region II. This is the region where one finds signals which corresponds to defects i.e. high decorrelation rates due to local imperfections that contains water or fluid. Region III is a region that since relatively long time was dry. In such a region, the fluid has evaporated both from the flat surface and from any surface porosity and defects can not be detected.

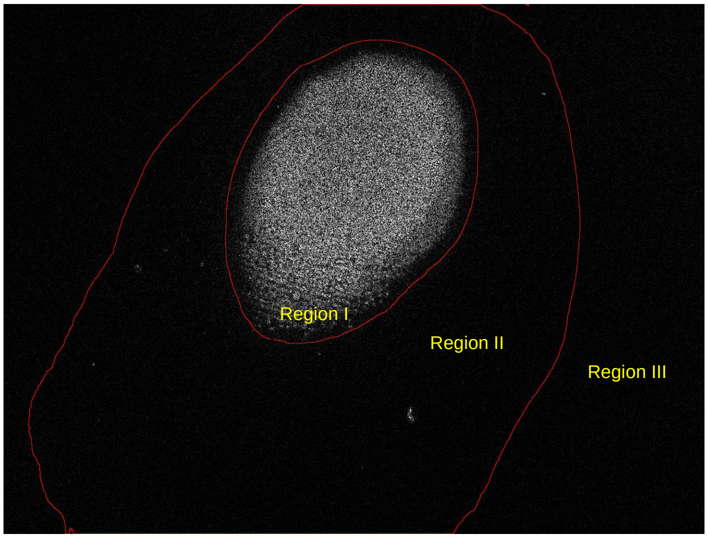

Fig. 4: Results from analysis of decorrelation rate according to Eqn. 2

Our current experimental configuration is equipped with an in-house developed analyzing software that uses information from the three regions in Fig 4 to gather and analyzes the results from a single measurement sequence. The procedure is to take the results from 4. and then …

5. Determine if the decorrelation rate of an individual pixel is obtained in an area which is covered by fluid or is dry i.e. if it belongs to region I or regions II or III. If it belongs to region I then it is discarded from further analysis.
6. Comparison of previously analyzed results facilitates a distinction between dry areas that belongs to region II (recently dry) or region III. Region III represent areas that have been dry for a long time and hence are not interesting and therefore discarded from further analysis.
7. Region II contains interesting and useful results. These values are superimposed on to a master image
8. steps 3. to 7 are repeated until the master image contains information from the entire observed area
9. Surface defects are identified from the master image as the areas (subimages) where distinct bright spots are surrounded by darker areas.

Different evaporating fluids have been considered, ranging from fast evaporating fluids and solvents like methanol and acetone to various forms of water based solutions or air saturated with moisture. Different methods to apply fluid on the substrate were also considered like e.g. dipping, spraying, wiping or distributing with a saturated cloth. All methods work in principle although it was seen that it was easiest to obtain thin films of fluids by using a saturated cloth. It was also noticed that the best ways to obtain a homogeneous and quickly evaporating film of an environmental friendly media was to breathe on the substrate and follow the subsequent evaporation of the condensed film.

3. EXPERIMENTAL UNIT

While the ultimate goal is to produce and make the "DETECT" system useful for online measurements in a production process the current system is made to work as an off-line experimental unit. The hardware that was developed consists of two major units 1) a unit that distribute fluid or moisture on the substrate and 2) the image analyzing unit.

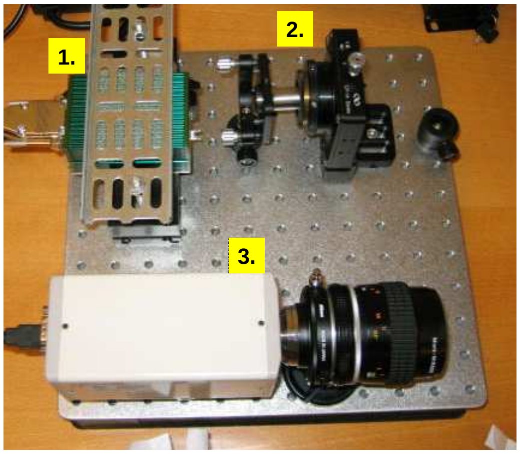

Fig. 5: Components of image analyzing unit

The image analyzing is depicted in Fig 5. It consists of (1.) a Cobolt Samba 532nm Nd:YAG laser with output power of 100 mW. A package of optics (2.) is placed in the optical path of the laser beam. The optics consists of a 10x microscope objective that focus the beam into and through a 25 µm large aperture. The resulting divergent laser light is further spread and distributed as it passes a lens on its way to the illuminated object. (3.) A CCD-camera, Hamamatsu, C8484-05G with 1344 x 1024 pixel resolution, and a Nikon 55 mm camera objective continuously observe the illuminated surface. The camera continuously feeds a PC with images - similar to the one depicted in Fig 3. - at an approximate rate of 1 Hz. The PC uses an in-house developed software to perform the decorrelation calculations and defect detection algorithm on-line. All the optics is mounted on an optical breadboard with a dimension of 300x300x59 mm^3. Attached to the breadboard is also a mechanical connection that permit mounting of the unit on a tripod.

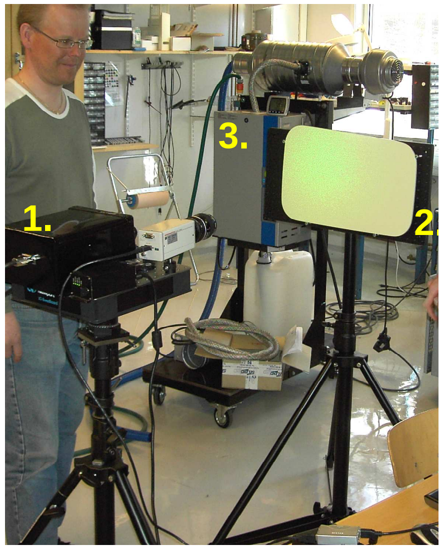

Fig. 6: Components of image analyzing unit

A special unit that distributes moisture on the substrate was also constructed and built. The unit was designed to produce air with similar temperature and level of saturation as the human lunge, since this empirically was found to work very satisfactory. A unit originally indented for the use as steam generator in a sauna is used to generate the steam. This steam is directed into a tubular mixing zone where it is mixed with fresh air. The amount and rate of fresh air is controlled by a fan that also provides pressure to drive the saturated air and moist mixture through a flexible hose. The flexible hose is used to direct the air stream on the substrate. The unit is shown and indicated as item (3) in the picture shown in Fig 6. The picture also shows the image analyzing unit (1) mounted on a tripod and the SMC substrate (2) also mounted on a tripod.

5. EXPERIMENTAL RESULTS

To demonstrate a proof of the capability of the unit and the method to detect real defects on SMC substrate one can notice the three white areas in Fig 7. These areas indicate areas with high decorrelation rate during a measurement. The areas are denoted and numbered by Defekt 1 to 3 respectively.

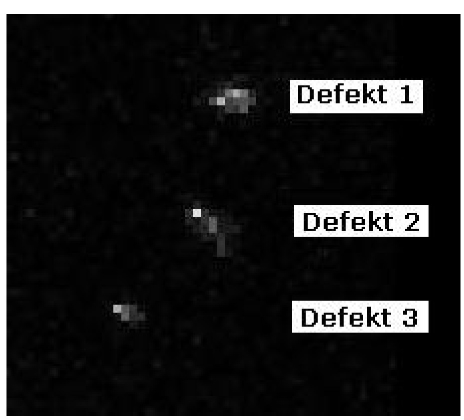

Fig. 7: Areas of high decorrelation rates during a trial on SMC substrates with visual surface defects

The substrate analysed in Fig 7 was cut and cast in epoxy resin after the measurement. These specimens were then gradually polished and analysed with optical microscope. The resulting micrographs are presented in Figures 8 to 10. By careful polishing we were able to obtain several micrographs of each defect, thus providing an idea of the 3D-geometrical configuration of each of the identified defect. From the micrographs it is evident that each area that has a bright appearance in Fig. 7 corresponds to area occupied by a significant defect that combines a certain size and volume beneath actual substrate surface and an open hole that is exposed to the surface. The identified defect had a geometry and size of approximately 100 to 150 μm at the surface. Underneath the surface the defects were considerably larger with a quite complex geometry. From the results with "DETECT" it was qualitatively noticed that defects with a large volume in the interior of the material generally produced more visible and distinct indication with the "DETECT" unit.

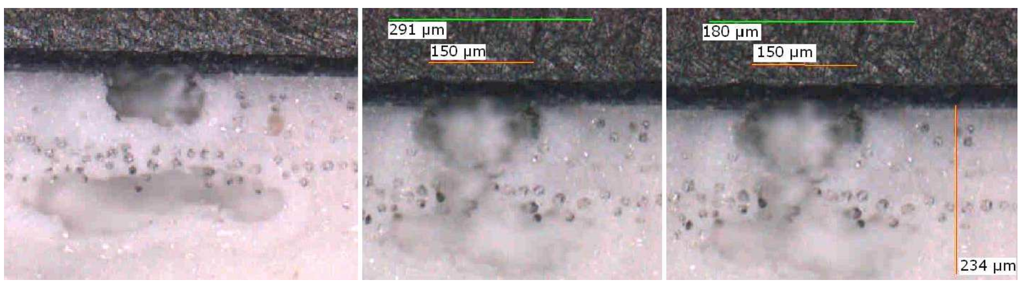

Fig. 8: Micrographs showing polished cross-sections of Defekt 1

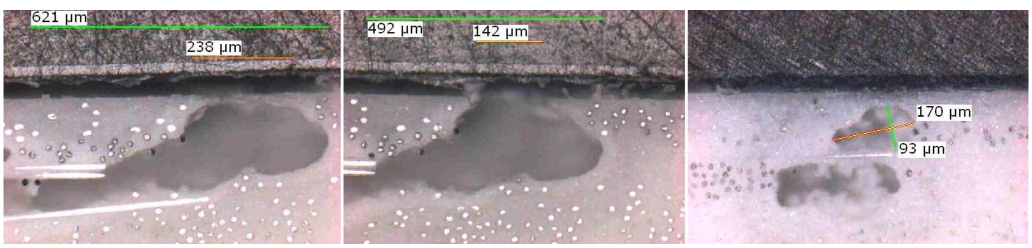

Fig. 9: Micrographs showing polished cross-sections of Defekt 2

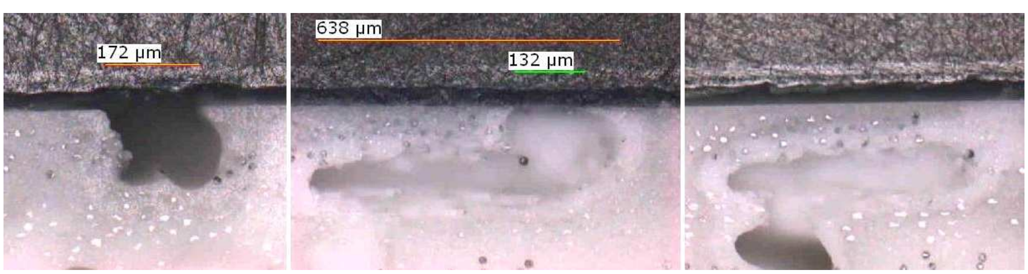

Fig. 10: Micrographs showing polished cross-sections of Defekt 3

The "DETECT" measurement unit was also used to perform a series of measurement on a flat SMC part. The part can be seen in the photograph in Fig 6. It is an exterior panel on certain truck models produced by Scania AB. The part we considered were taken out from the production flow prior to painting since surface defects was visually observed. A majority of the defects on the plate were defects within the so-called in mould coating (IMC) [3] layer. The IMC is a coating compound that is injected and cured on the mould surface prior to actual pressing and processing of SMC parts. The purpose of the IMC is to prevent surface porosities.

An area of size 188 x 144 mm^2 (width x height) was observed during the measurements. The camera and hence the images supplied to the "DETECT" algorithm has a resolution of 1344 x 1024 pixels. Each pixel thus corresponds to a 140 x 140 μm^2 large surface on the substrate. Two sets of experiments were conducted. The same area was observed during both sets. A total of 12 repetitions were performed during the first set and 19 repetitions were performed during a second set. The output from each measurement, with the current software configuration, is a text file containing the position and size (in number of pixels) of all the surface defects that are registered. The total number of registered defects ranged from 20 to 57 for 28 out of 31 repetitions. Three measurements gave significantly higher number of defects (105, 138 and 172 defects). These three are significantly higher than the others and are considered as artefacts and not included in the analysis. It should be emphasized that the total number of defects registered during a single measurement is to a large extent depending on the settings used in the calculations e.g. how different threshold values are set etc. The different settings were kept constant throughout all our measurements.

1). Number of defects counted manually

	1	2	3	4	5	6	7	8	9
A	0	0	0	0	0	0	2	2	0
B	0	0	0	0	0	1	0	1	5
C	0	0	0	0	0	1	0	3	5
D	0	0	0	0	0	1	0	0	5
E	0	0	0	0	0	1	0	2	3
F	0	0	0	0	0	0	0	4	2
G	0	0	0	0	0	1	0	8	2

2). Average number of defects by DETECT (28 repetitions)

	1	2	3	4	5	6	7	8	9
A	0	0	0	0	1	2	1	0	1
B	0	1	0	1	0	0	0	0	4
C	0	0	0	0	0	1	0	2	2
D	0	0	0	0	0	1	0	2	2
E	0	0	0	0	0	0	0	2	0
F	0	0	0	0	0	0	0	3	0
G	0	0	0	0	0	0	0	2	0

Fig. 11: Number of visually observed defects (upper) and average number with "DETECT" (lower)

We also investigated where the surface defects generally could be found and whether these locations corresponded to areas where visual defects were observed. The entire area was divided in to 9 x 7 = 63 sub-areas with approximate dimension of 20 x 20 mm. The number of defects in each sub-area was first manually counted and these results are presented in the upper matrix in Fig 11. A Matlab script was written that sorted and counted the text file generated by the “DETECT” measurement. The average number of defects in each zone is presented in the lower matrix of Fig. 11. It can be noticed that there is a certain discrepancy between individual zones but it is also evident that the general pattern indicates that the current version of the “DETECT” system is able qualitatively indicate in which areas defects are present.

The overall conclusion from the experiences and evaluation of the new method is that the method in generally is capable of detecting surface defects. At the same time it should be emphasized that the hard- and software is far from completely developed and optimized. A number of uncertainties still exist which makes it not possible to guarantee that reliable quantitative results can be obtained in a single measurement. One uncertainty originates in the observation that the output (i.e. number of defects) from the current system configuration was quite sensitive against variations in substrate, air and moisture temperature. The appearance of dust or dirt particles could sometimes give signals that mistakenly are interpreted by the system as defects. A feature of the measurement system is that it is sensitive against vibrations and relative movements between laser source, camera and substrate. In total it is believed that these uncertainties combines and contribute to the difficulties of having reproducible quantitative results from the current system configuration. One the advantage side one need to mention and emphasize that it is theoretically possible to detect flaws and pores that are of same size as one subimage (ideally 1 pixel) with the “DETECT” method. This is because the method utilizes changes over time to distinguish defects i.e. one more dimension – time – is added to the algorithm. Methods that use instantaneous images inevitable have to rely on image information with higher resolution. The possibility to study large areas at high rate and with high resolution appears to be better with the current method as compared to other optical methods.

6. SUMMARY

A novel optical method for detection of surface porosities on SMC substrates was presented. By building a pilot measurement unit it was shown that the principle ideas of the system work. A first attempt was also made to develop the pilot unit so that it could provide quantitative numbers of actual defects on an SMC substrate. The results are encouraging in the sense that it was observed that the semi-automatic unit can automatically identify areas with larger number of defects.

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REFERENCES

1. Sjögren, A., Finmnan A., Bernlind H., Lundemo C,. "An approach towards avoidance of pinholes and blowouts in painted SMC, 5th International AVK-TV Confernece, Baden-Baden, Germany, 2002.
2. Sjödahl M., Larsson L., "Monitoring microsructural material changes in paper through microscopic speckle correlation rate measurements", *Optics and Lasers in Engineering* **42**, 193-201, 2005.
3. Castro JM, Griffith RM, In-mould coating, In "*SMC Sheet Molding Compounds Science and Technology*", Kia HG (ed) (1993), Carl Hanser Verlag